REVIEWS OF GEOPHYSICS, SUPPLEMENT, PAGES 659-661, APRIL 1991
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1987-1990

Seismology in the U.S., 1986-1990

THOMAS H. HEATON
U.S. Geological Survey, Pasadena, California

In this volume, seven highly respected seismologists attempt to summarize seismological research in the U.S. in the past four years. This is indeed a daunting task; the mere compilation and classification of the overwhelming volume of new seismological literature is difficult enough, but to confidently provide an overview of our new knowledge and understanding is almost impossible. Although the study of vibrations in the Earth (that is, seismology) may at first seem to be a scientific field of limited scope, it encompasses a vast range of observations and problems in mathematical physics. Seismologists currently study waves varying in frequencies from 10^2 Hz to 10^{-4} Hz (20 octaves) and in acceleration amplitudes from 1 g to 10^{-12} g (240 dB). These waves are observed at a wide variety of distances as they travel through a very complex medium, the interior of the Earth. Furthermore the waves are excited by numerous and often complex mechanisms, including earthquakes, man-made explosions, landslides, volcanoes, and atmospheric disturbances. Seismologists study waves from earthquakes that range in energy over 15 orders of magnitude. These waves are studied to reveal the physical properties of the Earth, the kinematics and dynamics of Earth deformation, the characteristics of destructive earthquakes and volcanoes, and the occurrence of man-made explosions. When viewed from this perspective, it is little wonder that any individual seismologist can feel overwhelmed by the sheer volume of seismological research in the past four years.

Several thousand seismological papers were published in the past four years; Langston (this issue) alone lists 800 papers pertaining to wave propagation problems. I confess that I have only read a small fraction of these, and even if I had read them all, I would not attempt to choose those having the greatest significance. Instead, I can only summarize current trends in seismological research.

SEISMIC DATA RECORDING AND DISTRIBUTION

Seismology is primarily a data-driven science, and the past four years have seen important advances in existing systems to collect and manage seismic data, as well as the implementation and planning of new systems. There are currently about 1,500 short-period stations included in the numerous telemetered regional networks in the U.S. These networks were mostly deployed a decade ago, and during the past four years there have been severe financial strains associated with their operation. Nevertheless, significant progress was made in solving nagging problems of data access, system calibration, and noise reduction. These regional networks currently record approximately 30,000 events each year with relatively high station densities. Although many researchers are utilizing the data from these networks for a wide range of studies, it is clear that only a small percentage of the enormous set of waveforms has been studied.

The past four years have also seen a steady growth in the number of recordings of strong ground motions. There are approximately 3,000 strong motion accelerometers in the U.S. and important new data sets were collected for the 1 October 1987 Whittier Narrows earthquake (M 5.9), the 24 November 1987 Superstition Hills earthquake (M 6.6), and the 17 October 1989 Loma Prieta earthquake (M 7.1).

Perhaps the most dramatic development in observational seismology is the deployment of very-broad-band stations. Although very-broad-band seismometers were developed over a decade ago, it has only been in the last several years that they have been recorded with 24-bit data loggers. These systems record ground motions over an unprecedented bandwidth (0.2 sec to 10,000 sec.) and dynamic range (140 dB). Furthermore, data can be rapidly retrieved via telephone and computer networks by any interested researcher within hours after the occurrence of a significant event. The deployment of these stations is accelerating; the Incorporated Research Institutions for Seismology (IRIS) have deployed eight of these stations to date (not as many as they hoped). The deployment promises to accelerate in the coming years as IRIS proceeds with their plans for a 100-station Global Seismographic Network. The U.S. Geological Survey is also well along in its plans to deploy a similar 100-station network (the National Seismic Network) within the U.S. Individual universities are also implementing plans to deploy these very-broad-band stations; there are currently six of these stations operating in southern California resulting from a grant from the Whittier Foundation to the California Institute of Technology. The data from this new generation of very-broad-band stations promise to revolutionize the study of seismic waveforms recorded at both teleseismic and regional distances.

A similar revolution is also occurring in the deployment of portable digital data loggers. Despite funding levels well below those originally planned, the Program for Array Studies (PASSCAL), a program of IRIS, has proceeded with their plans to deploy up to 1,500 digital recorders in several distribution centers in the U.S. These portable systems are designed for recording waveforms for a variety of purposes, including aftershock studies, refraction and wide-angle reflection studies, and reflection profiling. In the past four years, PASSCAL has progressed from a set of design goals to the deployment of their first 90 systems, which are currently maintained by the first regional

Paper number 91RG00728.

PASSCAL instrumentation center located at the Lamont-Doherty Geological Observatory.

In the past four years, we have also seen a remarkable improvement in systems to provide access to large digital seismic data sets. Developments in digital storage and communications technology have allowed the implementation of long awaited systems that provide convenient access to large data sets. Although the developments are too numerous to list in this introduction, there are a few especially noteworthy developments. In particular, the National Earthquake Information Center (NEIC) has distributed CD-ROM's with waveforms from larger worldwide events recorded on the Global Digital Seismic Network (GDSN) for the time period from 1978 to 1986. They have also distributed a CD-ROM with compilations of phases collected by the International Seismic Centre (ISC) and a CD-ROM with a collection of numerous different earthquake catalogs. IRIS has also begun operation of its Data Management Center (DMC) which provides near real-time access to digital seismograms from the Global Seismographic Network.

RESEARCH

Seismologists have long recognized that there is great diversity in the wavefields that propagate in the Earth. This diversity can only be explained by spatial heterogeneity in Earth properties and by spatial and temporal heterogeneity in seismic sources. Characterizing these heterogeneities, either statistically or deterministically, is a common theme in seismology for at least the past decade. Inversion is the most common tool used to explore the heterogeneous nature of many seismological problems, and a trend continues towards ever more complex and sophisticated inversion studies. Dramatic improvements in the digital recording, communication, and analysis of seismic data have made detailed inversion of large waveform data sets a familiar tool for imaging Earth structure and earthquake sources.

As digital waveform data have proliferated, so has development of techniques to synthesize waveforms resulting from propagation through complex media. As can be seen in the reference list of Langston (this volume), there has been a tremendous effort expended to interpret the information contained in waveforms. Although new techniques have been developed using generalizations of ray and mode representations of wavefields, finite difference calculation of wavefields in heterogeneous media (both 2- and 3-dimensional) is also becoming a common technique for investigating these problems.

Knowledge of the overall seismic velocity structure of the Earth's interior is of fundamental importance; it provides important constraints on the variations in density and rheology that are the engine for our dynamic Earth. It has been a decade since the first serious attempts to map the three-dimensional velocity structure of the Earth, and work on this problem has steadily increased ever since. Although this problem seems far from being adequately solved, Masters (this issue) concludes that there has been a general convergence in models of the large-scale velocity structure of the mantle. Mapping the anisotropic and anelastic properties of the Earth's interior has also been a subject of considerable interest in the past four years, although it still seems too early to have formed a consensus about the spatial distribution of these properties.

The nature of wave propagation in the structurally complex Earth's crust has also been a subject receiving great attention. Crustal wave propagation is a subject of fundamental importance to studies of seismotectonics, strong ground motion, source physics, and nuclear detection. The past four years have seen large scale crustal imaging experiments that were organized by multi-disciplinary and multi-institutional consortia. Some notable examples are (1) PASSCAL projects in the Basin and Range, the Ouachita Mountains of Arkansas, and the Brooks Range of Alaska, (2) the CALCRUST project to image crustal structures of California including the Whipple Mountains, the Tehachapi Mountains, the Mojave Desert, and the East San Francisco Bay, (3) the GLIMPCE project to image the structure of the Great Lakes, (4) the PACE transect across southern California and Arizona, (5) the TACT project in Alaska, and (6) the EDGE transects extending from the continental margin and into the central part of California. The proliferation of these large experiments to map crustal structure is an exciting new development in seismology that is yielding new insight into the overall structure of the crust.

Understanding earthquake sources is of fundamental interest for many fields of Earth science. The study of earthquake sources helps define active deformation processes, it provides important constraints on the state of stress of the crust, and it is of primary importance to understanding and predicting strong ground motions. Following trends established over a decade ago, it is now commonplace to invert teleseismic waveforms to derive a set of point-source force-couples (i.e. moment tensor) and their time histories. Ironically, in the past four years several researchers have shown that for heterogeneous media, the parameterization of earthquake sources with equivalent force couples leads to fundamental ambiguities.

Inversion of waveform data to map the temporal and spatial distribution of earthquake slip has also become a relatively common practice. These studies are showing that slip is often quite heterogeneous on a fault plane. There is also a growing body of evidence to indicate that the duration of rupture at any point may be surprisingly short compared to the time necessary for rupture propagation (at least for many shallow crustal earthquakes). The physical explanation for the spatial variability of slip and the apparent short duration of slip in earthquakes has fundamental importance to many problems; what is the distribution of stress and strength in the crust? How do they vary in time? Do earthquakes repeat in a characteristic fashion? Extremely fundamental questions have been explored in the past four years and no consensus has been reached about their answers, although there have been some very thought provoking models proposed (see Brune's review in this volume).

Recent studies indicate that several classes of mechanical models may be necessary to explain earthquakes. Convincing evidence has been presented that there is a class of "silent" earthquakes with durations of tens of minutes that excite anomalously large long-period waves (these may be more common at oceanic ridges). Finally, evidence was presented that explains deep earthquakes as a result of changes in material properties caused by very rapid phase transitions of metastable minerals.

There have been some significant earthquakes in the past four years. Considerable attention has been focused on the problem of blind thrust faults which may experience large earthquakes but which may not have a surficial fault trace. The 1987 Whittier Narrows earthquake (M 5.9) led to recognition that there are active blind thrusts beneath metropolitan Los Angeles, the second largest city in the nation. The 1987 earthquake ruptured only a small part of the extensive fault system inferred to exist at the periphery of the Los Angeles basin and fundamental questions about earthquake risk in Los Angeles remain unanswered.

The 17 October 1989 Loma Prieta earthquake (M 7.1) was probably the most important earthquake in the U.S. in the past four years. It was the most damaging U.S. earthquake since at least the 1971 San Fernando earthquake (M 6.5), and the excellent seismic data sets recorded for the Loma Prieta earthquake have already been the subject of many papers. The weeks following the earthquake were times of great excitement for seismologists; it appeared that a major earthquake had occurred (as anticipated) in a widely recognized seismic gap on the San Andreas fault. In 1988, the National Earthquake Prediction Evaluation Council had endorsed a report that relied heavily on the hypothesis that characteristic earthquakes repeat in a regular way. This report concluded that the single most likely earthquake in the San Francisco bay region was a M 6.5 earthquake on the Santa Cruz mountains segment of the San Andreas fault. Following the release of that report, M 5.1 and M 5.2 earthquakes occurred beneath the Santa Cruz mountains in June 1988 and July 1989, respectively. At the advise of earth scientists, the California Office of Emergency Services issued public advisories that, because of their location, these events might be foreshocks to a larger earthquake within 5 days. Although it was another two months following the second advisory until the Loma Prieta earthquake occurred, it seemed to many seismologists that this earthquake had in many ways been forecast.

Now, after a year of more careful study, many researchers are questioning whether the Loma Prieta earthquake was the earthquake forecast in the 1988 report. In particular, there is growing evidence that the 1906 and 1989 earthquakes may have been on separate subparallel faults, and that the repeat time for earthquakes similar to the 1989 earthquake may be larger than several hundred years. Ironically, while the Loma Prieta earthquake seemingly fulfilled the forecast of a characteristic earthquake, it provided evidence that earthquakes may not be characteristic and that forecasting their occurrence may be even more difficult than previously believed.

While there was considerable discussion about the predictability of the Loma Prieta earthquake, there was little question that many of the effects of such an earthquake had been anticipated. Although this earthquake was located 60 km from some heavily damaged sections of San Francisco and Oakland, these damaged areas were almost always associated with soft soils or mud that amplified ground motions or that failed due to liquefaction. There is thus a growing belief that locations that are especially vulnerable to earthquake damage can be identified, and perhaps the appropriate land use decisions can be made. At the same time, there was also the sobering thought that earthquakes similar to the 1989 Loma Prieta earthquake will someday occur directly beneath the metropolitan areas of the San Francisco bay region, an occurrence that will almost certainly cause far greater damage than occurred in 1989.

Finally, there is the Parkfield characteristic earthquake (M 5 $^3/_4$) that did not occur in this reporting period. As reported by Bakun in the last U.S. National Report, numerous geophysical instruments have been deployed and prediction plans have been developed in anticipation of this event that was estimated to have a 95% chance of occurring within a 10.4-year period centered on January 1988. The Parkfield prediction was made assuming the regular repeat of nearly identical characteristic earthquakes. However, as has happened with the Loma Prieta earthquake, researchers are questioning just how similar past Parkfield earthquakes have been and whether our current understanding of the conditions necessary for earthquake rupture are adequate to allow meaningful predictions based on the time of the last earthquake. The debate over characteristic earthquakes is far from settled and its resolution has profound implications for our basic understanding of both earthquake risk and the fundamental physics of earthquake processes.

I would like to thank John Anderson, Larry Braile, Jim Brune, Egill Hauksson, Chuck Langston, Guy Masters, and Brian Stump for their comprehensive and thoughtful papers included in this volume. I also thank Ralph Archuleta, Fred Followill, Art Frankel, Niel Frazer, Gary Fuis, Dave Harkrider, Don Helmberger, Hiroo Kanamori, Thorne Lay, Walter Mooney, Jim Mori, Dave Oppenheimer, Paul Richards, Paul Somerville, Paul Spudich, and Toshiro Tanimoto for their reviews of manuscripts. Finally I thank Linda Rosenthal Curtis for her patient help with coordinating this report.

Thomas H. Heaton, U.S. Geological Survey, 525 S. Wilson Ave., Pasadena, CA 91106.

(Received February 1, 1991;
revised March 1, 1991;
accepted March 1, 1991.)